STUDIES FOR STUDENTS

RELATIVE GEOLOGICAL IMPORTANCE OF CONTINENTAL LITTORAL, AND MARINE SEDIMENTATION

JOSEPH BARRELL
Yale University, New Haven, Conn.

PART III. MUD-CRACKS AS A CRITERION OF CONTINENTAL SEDIMENTATION

INTRODUCTION

The previous parts on the relative geological importance of continental, littoral, and marine sedimentation have shown that the bulk of present sedimentary deposits are formed either upon the land or beneath the sea, and that the littoral, restricted to its distinctive

limits as that belt of shore exposed between the highest and lowest monthly tides, forms but a relatively narrow transitional zone. Furthermore, it was shown that the chances for preserval of the true littoral deposits are but slight, for if the land is upraised, they are the most superficial deposits and the first to suffer erosion. If the land is slowly sinking, the margin of the sea moving across the land planes away the deposits made in advance of it to the limits of wave action, and this is ordinarily greater than the depth of the littoral deposits. Under these conditions the unlithified deposits formed in advance of the transgressing sea will only be preserved where protected in some manner from the work of the waves which follow.

The most favorable places for the development and also for the preserval of a broad littoral zone were found to be the frontal portions of the larger river deltas. In such places it has been seen that a slow subsidence frequently takes place *pari passu* with the accumulation of river-borne sediment, but the sea does not advance inland, and the littoral deposits are therefore not destroyed, but finally become buried to depths where they are beyond the reach of surface agencies and hence indefinitely preserved. But even in this case the littoral deposits form but a transitional zone between much more extensive and equally well-preserved marine deposits on the one hand and continental flood-plain deposits on the other.

It was furthermore shown that a considerable portion of the sediment of rivers was deposited not beneath the sea, but upon deltas facing and encroaching upon waters of the oceans or their outlying seas. This subaërial deposit of river waste upon deltas not only stands an excellent chance of preserval and incorporation into the geological record, but is ordinarily more important in area and volume than that of the littoral zone which borders it on the seaward side, and becomes most important where the deltas are broadly developed in shallow seas, since the deposits upon the delta surface hold under such conditions, a greater ratio to those deposited in advance of the delta. Even disregarding other important forms of continental deposits, the magnitude of subaërial deltas and the relatively small quantity of the littoral deposits which will be preserved indicate that a much larger place should be given to fluvi-

atile deposits in the geological record and much less to littoral than has been customary in the past.

In that article the distinctive features of the marine, littoral, and continental deposits were incidentally mentioned, as well as the features which they held in common, but the purpose was not to give criteria for their distinction so much as to discuss the relative areal and volumetric importance which they should assume in ancient sedimentary formations deposited under various geographic and climatic conditions. It was urged, furthermore, that formations belonging to these three zones should be sharply discriminated and separated, not only because of the strikingly different conditions under which they were accumulated, but also because of the fundamental importance of such distinction in many problems of paleogeographic and paleobiologic geology.

The present article is supplementary, and it is proposed to take up the subject of mud-cracks as a distinguishing feature and to note to what extent and in what associations they should be expected to occur in various kinds of deposits. Such a discussion seems the more pertinent since in the absence of fossils there are many detrital formations in regard to which there is at present no unanimity of opinion as to whether they were formed by means of either one, two, or three of the following agencies, viz., aeolian, fluviatile, lacustrine, estuarine, or those pertaining to the open shallow sea. It is possible that there are still other formations which have been unhesitatingly ascribed to an origin in shallow seas which may have originated upon the continental surfaces, since on account of the dominance of marine deposition there has always existed a tendency in the absence of fossils of land-dwelling organic forms to ascribe to sedimentary formations an origin beneath the surface of the sea.

METHODS OF ORIGIN OF MUD-CRACKS

The closeness of resemblance between the mud-cracks which are of such frequent occurrence in ancient sedimentary formations of an argillaceous nature and the mud-cracks formed in modern drying mud flats is such that no other origin for these ancient structures has ever been, or seems likely to be, suggested, than that of exposure to the air. They may be formed in any fine-grained argillaceous

or limy deposits which upon drying shrink notably in volume. Deposits whose grains are predominantly of sand size cannot give rise to mud-cracks, since when wet the water stands in the pores, and the deposit does not lose markedly in volume upon drying, but only in weight. This limitation in regard to the necessary size of particles requires that the deposit should originate under very quiet waters, which are either removed by evaporation or slowly drained away with bottom velocities of less than a third of a mile per hour, since such a current will lift fine sand.

Mud-cracked surfaces are observed to vary much among themselves. Sometimes they inclose polygons a few inches across, sometimes a foot or more in diameter. In depth they may terminate within a few inches or they may pass downward as many feet. As factors governing the nature of the mud cracks may be mentioned the shrinkage ratio of the deposit; the porosity by means of which water may be conveyed upward by capillarity, tending to prevent shrinkage; the varying nature of the stratified deposit, the cracks not being able to pass through thick strata of sand; the thoroughness of saturation; the length of the period of desiccation; the temperature and dryness of the air. It seems that a thorough observational and experimental study should throw important light upon some of these relations by means of which certain of the conditions attending the formation of mud-cracks in ancient strata could be recognized.

It is possible that a definitive solution is not usually to be obtained on account of the number of the governing factors. But the solution should be narrowed to one of two or three alternatives. For instance, providing that an argillaceous formation is homogeneous throughout, the depth of the crack will probably vary roughly as the square of the time of desiccation. It will also vary with some power of the temperature measured on a centigrade scale, and with some power of the degree of dryness of the air. A knowledge of these values would enable one to say if certain mud-cracks could have been formed in the fortnightly interval between spring tides, or if a season or more of desert heat and dryness were necessary.

As a striking example may be cited the mud-cracks described by Gilbert which penetrate ten feet downward into the variegated shales of the Upper Shinarump of the Jura Trias where exposed

on the northern flank of Mount Ellsworth.[1] The formation of these mud-cracks was followed by a complete change of sedimentation at this point into the homogeneous sandstones of the Vermilion cliff group, so that it is quite certain here that the mud-cracks were not formed in the brief interval between two similar tidal invasions. So little is known, however, of the relations between the governing conditions and the characteristics of the mud-cracks that, in the absence of more data, this detailed subject cannot be profitably discussed, and the attention will therefore be turned to the various conditions under which they originate and the associated chemical, textural, and structural features which accompany them in each case.

Such conditions are observed to obtain first, over playas and temporary lakes of arid regions; second, upon the margins of interior lakes; since the latter are peculiarly liable to seasonal fluctuation in level; third, over many river plains as a result of the periodical floods in places where the surfaces are not covered with an arboreal vegetation; fourth, over the higher portions of the littoral zone, where mud-flats or tidal marshes are exposed to the air sufficiently long for the mud-cracks to originate. The littoral in the previous article has been limited to the level which is flooded on the average twice per month by the tides of the new and full moon, since above this limit the tidal flooding is in a manner accidental and occasional and only occurs during abnormally high tides or storms. Mud-cracks will therefore be formed also over an adjacent portion of the continental zone due to unusual elevations of the level of the sea.

CONDITIONS FOR TEMPORARY PRESERVAL OF MUD-CRACKS

Before taking up the detailed discussion of the conditions of origin, relation to other features, and final preserval of mud-cracks, it is desirable to state some conclusions which the writer has reached from observation and experiment upon the conditions necessary for the temporary preserval of the cracks until the stratum shall become buried and form no longer the surface layer.

Experiments were conducted first upon interstratified light brown silty clay and dark brown clay of Champlain age; the former smooth to the fingers, but giving a fine grit to the teeth; the latter

[1] *Geology of the Henry Mountains* (1877), p. 9.

perfectly smooth to the teeth. Second, upon a modeling clay giving a fine grit and third, upon clay from New Haven harbor, gray-black when wet, light gray when dry, giving a very small amount of fine grit to the teeth. Lack of time did not permit accurate soil analyses to be made of these types.

The Champlain silty clay, firm and strong when removed from the clay pit, was dried and then covered with water. Within from five to ten minutes a stratum half an inch in thickness would soften, swell, and begin to disintegrate, losing all coherency, turning to a creamy mud and the margins sliding down to the angle of repose. The clay and silty clay were then ground up, mixed in nearly equal proportions, allowed to settle in pans from water and dried in the sun. After becoming thoroughly dry and cracked, two out of three pans were baked over gas, one at a temperature up to 70° C., the other above 100° C. This was done in order to test the effects of drying at and beyond the most extreme temperatures of torrid deserts. Upon being covered with water, the swelling and disintegration took place as before, indicating that a mixture of equal parts of pure clay with silty clay would not preserve the stratum from disintegration, and that the highest ranges of temperature found in nature were equally ineffective. Upon drying, cracking, and then rewetting, the lines of the cracks are partly closed by swelling. The remainder becomes filled and veiled with a more fluid mixture, and upon redrying the cracks are established chiefly upon the same lines, indicating a weaker cohesion along the lines of previous cracks. The same feature was observed in the field after a rainstorm, the deeper parts of the cracks having been closed by swelling, but still forming lines of weakness; the upper parts blurred by the slaking of the mud. Upon wetting in the laboratory, adding a new layer, and redrying, the two layers adhered as a unit, and the cracks were twice as widely spaced. Those which formed, however, followed in general previous lines of cracking, and those cracks which did not reopen were still to a slight extent lines of weakness. Finally, the pure clay in strata half an inch in thickness was dried for a couple of weeks at ordinary temperatures, broken, and placed in water. They gradually softened in the course of an hour, but for days retained their sharp edges and showed no tendency to disintegrate, though swelling 5 per cent.

linearly upon the plane of stratification. When rubbed to a batter in water and allowed to dry and crack, the edges disintegrated and the cake softened more rapidly, indicating that the original closer-knit texture had given it superior resistance. Drying and baking up to the boiling-point did not affect the result.

The modeling clay was not baked, but, in all respects tested, behaved like the mixtures of Champlain clay and silty clay.

Finally in August, 1906, excellent opportunities were offered for observing the behavior of the unctious and sticky gray mud of New Haven harbor; a reclamation company building turf walls around many acres of salt marsh land, and pumping water, mud, and sand from the center of the harbor into these artificial reservoirs, the sediment settling and the water draining away. In this way from 6 to 20 feet of sediment were laid down under most favorable conditions for observation. It was found that from mid July to mid August beds of gray mud up to a foot in thickness, resting upon sand, had dried and cracked into irregular polygons 1, 2, and even 3 feet in diameter, the cracks opening from 3 to 4 inches.

Where the mud was thicker, the bottom was still soft, but the top was cracked. Where the water was still standing no cracks had formed, but upon the disappearance of the water they began to appear as wedge-shaped cracks, while the top clay was still soft to the hand and the bottom so fluid as to make walking impossible.

These cracks had formed and the clay underlain by sand had dried and hardened to the depth of a foot during an interval, as stated, from mid July to mid August, during which time the mean temperature was 71° F., the average humidity 0.83, the precipitation, in thirty-one days, 3.0 inches, ten days partly cloudy, and twelve days cloudy.

Rain had failed to efface these cracks, though washing more or less mud into them, especially when the cracks were still young and narrow and the clay not yet hardened. Reflooding by pumping was observed to soften the clay to the consistency of a stiff gelatine and expand it somewhat, but did not obliterate the sharpness of the cracks even in the course of days; and where mud or sand was washed over the surface, the cracks were permanently buried and preserved. Where filled with similar mud and redried, the filling may be detected,

even where the crack fails to reopen, by the interruption of the faint lines of stratification at the margins and a slightly marked weakness along this line. When this mud was beaten up with the water, dried quickly over gas and then recovered with water, the air rapidly escaping from the many minute bubbles produced an audible simmering, and the mud, originally so retentive of its form, soon fell into a mush. It was also observed that the dry natural clay was subject to a slight exfoliation upon rapid wetting. These facts point out the importance of close texture, obtained by slow subsidence and long standing under water before drying. This requires the moisture to be transmitted slowly, by capillary action, and allows the mass to expand as a whole.

The conclusions from these observations and experiments will doubtless be somewhat modified by more extensive observations in suitable regions, but may be preliminarily stated as follows:

A mud-cracked loam or silty clay, even when the sand particles are imperceptible to the fingers, is an unfavorable material for the preservation of its detailed surface structures, except possibly when remaining moist, so that but little swelling and exfoliation take place. Upon being wet by rain, the rapid swelling and disintegration of the surface stratum would turn the surface of such a deposit into a creamy mud, which, if remaining *in situ*, might preserve upon redrying blurred impressions of the previous cracks and other larger surface features, but which would be peculiarly liable to be swept away and intermingled with the detritus of the following flood similar to the one which left the material. Even if the flood sweeps down from the mountains upon previously unwet desert plains, the few minutes of wetting necessary would suffice to destroy the detail of surface features before a sufficient new layer of sediment could be laid down. This would seem to explain the mud-lakes into which many playas are transformed during the rainy season. Upon such a formation becoming lithified, the record of mud-cracks might be greatly masked, if not entirely obliterated. The development of joint planes, and even a faint cleavage, would add to the difficulty of detection. Where the finer details of the original surface are preserved, however, or the sharp surfaces of stratification between unlike laminæ, it would seem impossible that the mud-cracks could

become completely obliterated. This, therefore, may be a test as to their former presence or absence.

A pure clay, slowly subsiding from quiet waters, and wet sufficiently long to become compact upon drying, would retain its mud-cracks upon rewetting, either by rain previous to flooding or by the flood waters themselves. Such a clay, on account of its tenacity, resists erosion even by quite rapid currents, as is seen from the presence of occasional areas of sticky blue mud on relatively shallow and open parts of the coastal shelf. In case such a sun-baked clay is covered and its cracks filled by a similar layer, it should retain a clear record of the cracks, provided it possesses a well-defined bedding cleavage, since such a cleavage will be interrupted at the margins of the cracks. Such pure and massive clay deposits form, however, the rocks most susceptible to dynamic metamorphism, and a pressure cleavage, even if developed upon the bedding planes, would tend to mask any previous interruptions. Frequently, however, such clay deposits from standing water will be interstratified with more or less arenaceous deposits swept along the bottom by the rising floods. Such sandy wash filling the cracks of the previous clay layer would give a persistent record to the buried mud-cracks. If the sand be sufficiently coarse not to shrink markedly upon drying or swell upon rewetting, the combination of the two kinds of laminæ should give a maximum opportunity for the complete preserval of mud-cracks, footprints, raindrops, and other surface markings. It is noteworthy that this is the typical nature of those beds in the Triassic formations of the Connecticut valley which have preserved such a magnificent record of mud-cracks and footprints. Large portions of these formations, however, consist of rather massive sandy shales or arkoses, and in these the writer has not noted the occurrence of mud-cracks.

On the larger river flood-plains, such as that of the Mississippi, the soil survey of the Department of Agriculture has established three principal types, grouped under the Yazoo series and seven miscellaneous types. Of these ten types only two are clays. The Yazoo clay—a heavy, drab clay loam—occupies low areas back from the low, flat ridges which form the front lands near the stream courses. It is a frequent type of soil. The Sharkey clay is a stiff, impervious clay occupying the lowest portions of river bottoms

and subject to annual overflow. Both are characterized by sun-cracks—a characteristic not ascribed to the other types of soil. It is noteworthy that the purer clay, and therefore that more favorable for the preservation of mud-cracks, is deposited, not from flowing, but rather from stagnant back waters, the one at high-water stage, the other when the water-level is lower. Only a portion of the deposits of the larger flood-plains are, therefore, well fitted to retain surface impressions until buried, and this principle must be carried into the past.

It is seen that mud-cracks may originate in pluvial climates, but the thick mat of vegetation apt to form under such conditions would tend, wherever it existed by the binding action of the roots, to prevent cracks from forming. An arid valley climate, therefore, and abundant sediment would be more favorable conditions for the broad development of mud-cracks. Rock decomposition, rather than disintegration at the sources of supply, the mark of a pluvial climate, should, on the other hand, be favorable as furnishing a larger proportion of pure clay mixed with the coarser material.

In conclusion, it is seen that special conditions are necessary for a complete temporary preserval of mud-cracked surfaces even where continued sedimentation without intervening erosion occurs. In formations which show traces of mud-cracks it is to be anticipated that other, more or less argillaceous layers may also have been exposed to the air. Sediments swept along by broad, slow-moving waters will ordinarily possess too much loam for the good preserval of mud-cracks. But where the flood waters stand quietly before being drained away, or where the loam is strained out or settles at another place, the fine clay will settle, forming a deposit free from sand, and capable of retaining even the faintest markings made upon its drying sufrace.

MUD-CRACKS OF PLAYAS

Description.—The characteristics of these may be best appreciated by quoting from Russell's descriptions of the present and extinct lakes of Nevada.[1] Speaking of the ephemeral lakes forming either after the rainy season or even after a single storm he says:

[1] *The Physiography of the United States* (American Book Co.), Monograph 4, pp. 105–10.

Should the storm continue, the sheets of water in the valleys will expand, and possibly become many square miles in area. Such lakes are always shallow, and always yellow with mud in suspension. When the sun breaks through the storm clouds, evaporation becomes active, and the lakes gradually contract their boundaries, and perhaps in a few hours or in a few days are entirely dissipated. When the water has disappeared, absolutely barren mud plains remain, which harden under the sun's heat, and become cracked in all directions as their surface contracts in drying. The lake beds then have a striking resemblance to tesselated pavements of cream-colored marble, and soon become so hard that they ring beneath the hoof beats of a galloping horse, but retain scarcely a trace of his foot-prints.

Such bare, level mud plains are characteristic features of the greater part of the valleys of Nevada, and are known in Mexico and adjacent portions of the United States as playas. The lakes to which they owe their origin are termed playa lakes. . . . . The largest ephemeral lake of Nevada is formed during winter months on what is known as Black Rock Desert in the northwestern part of the State. This desert valley is irregular in shape, and has lateral valleys opening from it. Its length from northeast to southwest is over one hundred miles, and its average breadth twelve or fifteen miles. In summer it is almost entirely without tributary streams, except such as are fed by hot springs. In winter many brooks descend the mountains to the east and west; and the channel of Quinn River, which enters the basin from the northeast, is transformed into a veritable river. The course of this stream in summer is marked only by a dry channel, with an occasional water hole; but in winter it is flooded so as frequently to be impassable to a man on horseback, and has a length of upward of a hundred miles. Its waters then spread out on Black Rock Desert, and at times form a long narrow lake from 450 to 500 square miles in area. Although seldom over a few inches deep, it is impassable on account of the softness of the mud forming its bottom. Many times the "lake" is a vast sheet of liquid mud, and for this reason is known as "Mud Lake" by the settlers of the region. This name is not distinctive, however, as many other playas have the same name attached to them. . . . .

The winter lakes on Black Rock and Smoke Creek deserts, as in many other similar instances, do not occupy the entire valley bottom, but are surrounded by a broad fringe of what to the eye appears level land. This broadening tract is covered with sagebrush and other desert shrubs. In early spring many flowers beautify the ground, and fill the air with a faint perfume. The playas left by the desiccation of the lake, however, are always barren. Not a plant takes root in their baked and hardened surfaces. Where these mud-plains meet the surrounding areas clothed with desert shrubs, there is often a belt of ground that is soft and marshy in winter, and frequently retains something of this character after the lakes have disappeared. In summer it becomes white with salts brought from below by ascending water, and left on the surface when evaporation takes place. These efflorescent deposits become unusually abundant

about some of the hot springs, and are then apt to contain borax in addition to the sulphate and carbonate of soda, common salt, etc., which make up the bulk of such incrustations. . . . .

North Carson and South Carson lakes are of the playa type, but are more persistent than the lakes of Black Rock and Smoke Creek deserts. They sometimes hold their integrity for a succession of years, but evaporate to dryness during seasons of more than usual aridity. North Carson Lake is rudely elliptical in outline, and is from 20 to 25 miles across from east to west, and about 14 miles broad from north to south. That its depth is never over a few feet, has been shown by examining its bed when dry. . . . .

Hundreds of other inclosed basins, particularly in southern Nevada, are partially flooded in winter in a similar manner to those already enumerated, and become desert plains of hardened mud in summer. Various portions of the region surrounding Nevada, and especially those embraced within the boundaries of Utah, Arizona, and California, experience changes similar to those just described, and illustrate some of the most striking peculiarities of a region where the topographic and climatic conditions favor the existence of temporary lakes.

Numerous playa lakes are also found in Australia and in Africa, especially in the Kalahari, and may be looked upon as common features of desert regions where the regolith is not sufficiently deep and sandy to absorb all of the occasionally precipitated water. Playa formations are not necessarily accompanied by conspicuous saline deposits since the clay washed in, and subsiding each year prevents re-solution of the buried salts and may largely exceed them in quantity. The amount of salt will also depend upon the area of the playa to the catchment area and the extent to which ground water contributes. In old desert regions such as the Kalihari there may be thus wide playa surfaces where water stands for a longer or shorter period. Speaking of the Kalihari, Brewer states that "Lake Ngami is fresh in the rainy season, but covers much less surface in the dry season, and is then brackish; and the other lakes of this desert are described as brackish rather than salt."[1]

Nature of the geological records.—The preceding is a description of playa surfaces. In the absence of descriptions of partially eroded playa deposits seen in cross-section the following statement of the characteristics which they would presumably show when incorporated into the geological record must be to some extent deductive and open to corroboration by observation.

[1] Wm. H. Brewer, *Warren's New Physical Geography.*

Playas will be flooded with water partly by means of stream channels, partly by a general wash from the outside over the slopes, partly by a gradual rise of the water level flooding the surface from the inside. In places of inflowing currents, the cracks should fill up with sand and thereby permanently preserve the structure; in places where clay settles in from quiet water, the infiltration may be almost identically the character of the wall materials and the former presence of the crack therefore escape record. The water stands over the flat bottom in periods varying from a few days to a few years, according as to whether it is an evanescent playa or one dry only during an occasional year. The periods of desiccation will vary in inverse order. In general, however, it may be said that the playa bottoms become thoroughly wet for a depth of several feet and undergo some months of desiccation with the formation of deep mud-cracks. Where the deposits are perfectly homogeneous and result in massive saline clays there may be no permanent record of the cracks. As playas are characteristic of typically desert regions there is but little likelihood of the incorporation of an organic record, either of leaves, bones, or tracks. As embodied in the geological record playas should occupy the centers of flat basins in mature desert regions, and in that case their deposits may conceivably attain a thickness of several thousand feet as the mountains are gradually leveled off and their waste accumulated in the tectonic intermontane troughs. Such deposits as seen in cross-section would pass irregularly into marginal waste slopes of coarser material and these in turn end unconformably against the sloping walls of the buried portion of the mountains. Thus their basin nature and limited extent would be evident.

Unless protected, however, by an invasion of the sea or a change to a pluvial climate such deposits as well as the intermediate rocky barriers will gradually be removed by deflation, as Passarge has shown,[1] and the desert will pass into the stages of old age as exemplified by the Kalihari. Throughout this process of erosion shallow playas play an important rôle, since the occasional rains wash the surrounding waste into them and thus tend to maintain a level

[1] "Rumpfflächen und Inselberg," *Zeitsch. deut. geol. Gesellsch.*, LVI (1904), Protokol., pp. 193–209. Review by W. M. Davis, *Science*, N. S., Vol. XXI, p. 825.

surface. But such deposits must be very shallow since as soon as insolation and deflation have lowered the surrounding tracts these in turn become playa basins and the waste of the former one suffers removal.

Thus ancient playa deposits may be of importance in certain intermontane desert basins of the Tertiary or earlier periods, now suffering stream dissection and exposure, but those of topographically old deserts can be of no importance except possibly as the occasional surface veneer of an ancient continent, such as that of the pre-Cambrian, when it passes unconformably beneath the deposits formed by a marine transgression. In such an event, however, they would doubtless be partly destroyed through marine planation.

MUD-CRACKS MARGINAL TO INTERIOR LAKES

Description.—There are many regions of the world showing all transitions between true salt lakes and fresh-water lakes with perennial outflow.

Where evaporation does not quite balance the inflow of water there may be an occasional discharge, either at the end of the rainy season or only during a series of rainy years. Such lakes without being salt show fluctuating shores, usually very flat, since the water does not stand sufficiently long at one level for the characteristic beach slopes to form. Wide expanses, therefore, may become sun-cracked and thoroughly hardened before the next rise of the lake waters occurs and deposits over them another layer of clay.

Prominent examples of this class of lakes are Titicaca in South America, 80 miles long by 40 broad, and Lakes Tanganyika and Tchad in Africa. Lake Sistan in Persia with a breadth of 60 miles and a length of 100 has been known to go completely dry, while in occasional years during times of heavy flood it sends a stream of water down the Shila.

Nature of the geological record.—In some respects the structures recorded in the formation of the successive laminæ will be similar to playas, but differ in that the exposed area is a transitional belt between a relatively permanent water body and a permanent land surface with its wind and stream-borne detritus. It is more subject to wave-action, building occasional beaches; it may not be salt

and may be the seat of a considerable assemblage of living forms. The result is that the lake clays need not be saline, but are likely to be leached of iron or be even carbonaceous and fossiliferous. Foot-prints may also be common on the shores and the remains of land plants, and animals may become entombed in the deposits. The wash of nearby land waste and the action of waves may fill up the mud-cracks with sand and thus lead to their permanent preservation.

Interior seas are unstable bodies whose shores are ever varying, and which are finally destined to be either dried up into playas, the fate of Lake Lahontan, or to be filled up with sediment, giving rise to river flood-plains, the fate at present overtaking Lake Titi-caca, or by becoming fresh to be drained by cutting down an outlet, a change at present in progress in several of the large African lakes.[1] As seen in geological section the mud-cracked margin should be transitional on any one horizon between fine-grained, paper-thin, lake clays, on the one hand, showing no mud-cracks, and the coarser slopes of land waste on the other. In ascending through the formation such mud-cracked shales should oscillate laterally and occupy but a portion of the series. They could hardly, therefore, be a characteristic feature of the sediments in general, nor even of the bodies of shales originating in the lakes of interior basins.

MUD-CRACKS OF RIVER FLOOD-PLAINS

Description of present conditions.—Over all river flood-plains inundations periodically take place, and as the flood waters gradually drain away, a large quantity of fine mud is left upon the surface, perpetually renewing the fertility of the soil. Where the climate is humid, as over the delta of the Mississippi, such regions become seats of luxuriant verdure, while on the contrary in arid or semi-arid regions, an evanescent vegetation may spring up following the flood, but as soon as the water is drained away and the level of the ground water sinks beyond the reach of the plant roots the region becomes a desert until the period of the next inundation. Such regions are abundant over the desert belt of the world, the flood plains of Egypt, of Mesopotamia, and of the Indus River being

[1] Albrecht Penck, "Climatic Features in the Land Surface, *American Journal Science*, Vol. XIX, p. 171 (1905).

familiar examples.[1] In such regions the conditions of mud-crack formation are at a maximum and may extend to the margin of the littoral zone.[2] Consequently carbonaceous deposits and mud-cracks both mark the land surfaces of aggrading rivers, the one a maximum in pluvial climates, the other in arid. Mud-cracks, as contrasted with coal beds, may thus serve as an index to ancient climates as well as possessing a stratigraphic significance.

In applying this distinction to the earlier geological periods it should be held in mind, however, that there is no evidence of an arboreal or even herbaceous vegetable covering to the land previous to the Silurian, and its surface was presumably devoid of life save possibly that of the lowest cryptogams. Under such circumstances the indications of the presence of former flood-plain surfaces by means of carbonaceous deposits or deoxidizing effects upon the ferric oxide might be entirely absent. Mud-cracks would be the safest remaining indication of the flood-plain nature of the land surface over the regions where the character of the detritus was suitable and periods of desiccation were sufficiently long for the formation of the cracks and hardening of the successive surface layers.

The necessary fineness of deposit is frequently not found on the sandy or gravelly fans of mountain streams, and hence a large per cent. of stream-built deposits could not be expected to show this feature. The necessary conditions are found, however, on all streams of small gradient which broadly overflow their channels, this being characteristically the case of the larger rivers in the lower portions of their courses and especially over the delta, where the argillaceous nature of the deposits is well known. Broadly speaking then, the formation of mud-cracks is non-essential on slopes of piedmont river waste, but is especially characteristic of the larger river plain and delta deposits of arid and subarid climates. That the phenomenon is not strictly confined to even subarid climates is, however, true since humid climates may have their seasons of dryness.

[1] See for illustration, Daniel Trembly Macdougal, "The Delta of the Rio Colo rado" (with map by Godfrey Sykes), *American Geographical Society*, Jan. '06.

[2] Walther, *Das Getz der Wüstenbildung*, 1900, also mentions the occurrence of mud-cracks on arid flood-plains. See *Trockenrissen* in index.

Nature of the geological record.—Flood-plains differ from playas and the shores of interior lakes in important particulars. Playas are formed in local basins or as the ends of desert rivers, usually of limited length. Playas do not fill up valleys from which the rivers escape, but are entirely phenomena of interior drainage. They are not built out against the sea and the deposits are at least brackish from the inclosed salts.

The flood-plain of an aggrading river covers a wide area, in the case of the larger rivers measured by thousands of square miles. It is all periodically subject to inundations which may last for a few days or weeks, but leave the greater part of the surface exposed to the air during much of the year. The invading flood waters frequently sweep sand with them, but after the flood is at its height the waters drain away quietly and much of the fine clay is deposited from suspension. Thus on river flood-plains there is peculiar liability to form well-interstratified deposits of sand and clay: to fill up the last-formed mud-cracks with coarser material, and hence permanently to record them through the varying composition and structure of the formation. Such successive strata of the same nature may be indefinitely accumulated.

Such valleys even in desert regions commonly support considerable life. Drifting vegetation is liable to become buried and animals crossing the half-dried flats in search of fresh water may leave through their foot-prints a record of their visits. The periods of desiccation are seasonal and sufficient to harden this record of cracks, rain-prints, and foot-prints to such an extent that the next invasion of water does not wash it out, but by depositing upon it a new layer of sediment permanently preserves it. As the main streams or their distributaries wander over the plain from century to century they form a network of channels-which cut through the preceding fine-grained layers of the flood-plains, and the channels become filled with sand or even gravel, as they are finally abandoned for new courses. They may be distinguished from the beach sands and gravels of lakes from their linear, treelike arrangement, their occasional cutting-down into the finer-graind layers, and their occurrence far from the margins of the basin.

The mud-cracked strata of flood-plains not only stand excellent

chances of temporary preserval until buried, but since the surfaces upon which the fine-grained river waste is deposited are ordinarily near the level of the sea and are also in the case of the greater deposits frequently regions of subsidence, the chances for ultimate preserval of the bulk of the formation is, in such cases, as favorable as that of the true marine shallow-water deposits.

Again, flood-plain surfaces are not of a transitional or temporary geological nature, like the margins of interior lakes, or the borders of the sea, but they are the ultimate physiographic forms toward which both lakes and shallow seas tend by the filling-in of river waste. They are of broad occurrence at all times of continental extension and erosion, and should be looked for in the geological column as only second in importance to the off-shore deposits of the continental shelves and seas. But although flood-plains are most commonly built near the margins of the land and encroaching as deltas upon shallow seas, they are also found to occur over the regions of gräben or troughs of subsidence, such as those of the Rhine, and of other tectonic valleys, and also over interior basins. Murray has estimated the desert areas, that is those which do not drain to the sea, as one-fifth of the continental areas. Doubtless, at least another fifth is possessed of a climate marked by sufficient seasons of drought to allow the broad formation of mud-cracks upon flood-plains, following the subsidence of the flood waters.

This natural condition is, however, largely modified at the present time by the agency of man, since, by regulating the floods and by systems of irrigation, such regions become the seat of populous societies. It has been shown in the previous article that the deposits of flood-plains should enter more largely into the geological record than is usually appreciated. Combining this conclusion with these considerations in regard to climate it is seen that in those past times, which corresponded in general to present conditions, an appreciable fraction of argillaceous deposits should be characterized by mud-cracks formed upon flood-plains, and, on the other hand, in regions where the mud-cracks of the period are missing, another appreciable fraction should by their carbonaceous and organic contents bear witness of the verdure which prevails upon the river plains of pluvial climates.

Besides these general stratigraphical relations which should characterize the mud-cracked deposits of arid flood-plains may be mentioned other associated characteristics, some of which are pointed out by Walther.[1] Such deposits are usually rather barren of fossils of water-living forms; the latter, if present, are apt to be restricted to the lines of sandstone which mark the ancient channels[2] or to the deposits of shallow lagoons. The flood plain proper is more likely to contain the remains of air-breathing forms, but as conditions must have been frequently unfavorable for their life or for their preserval after death the strata are more usually barren.

Further, land deposits on account of the local and annual variations of conditions are apt to show various sorts of deposits—water borne, wind borne, organic, and volcanic, in close association but differentiated from each other. Marine deposits are not subject to this rapid variation and more gradual transitions are observed.

Deposits formed in rivers or in lakes and seas have usually greenish or bluish shades of color as in marine deposits. Those subjected to subaërial exposure, however, under arid or subarid conditions are apt to possess a normal content of iron owing to the absence of carbon and the opportunity for complete oxidation following the subsidence of the ground water. The river muds from which the iron has not been leached by the deoxidizing influence of vegetation may thus be yellow, brown, or red. In well-lithified but still unmetamorphosed formations, in which the iron still exists in the form of a free oxide, reds predominate, whereas in modern muds derived from the crosion of granite lands yellow or brown is observed to be the prevailing color. But Crosby[3] has shown that a gradual dehydration of the ferric oxide serves to transform colors originally yellow and brown into deep red or vermilion.

River deltas normally contain abandoned channels or lower tracts of country not yet built up which are more or less permanently flooded with fresh water. Such are usually the seats of luxuriant vegetable growth and abundant animal life, even under climates where the

[1] *Einleitung in die Geologie* (1893), pp. 719–26.

[2] J. B. Hatcher, "Origin of the Oligocene and Miocene Deposits of the Great Plains," *American Philosophical Society*, Vol. XLI (1902).

[3] "On the Contrast in Color of the Soils of High and Low Latitudes," *American Geologist*, Vol. VIII (1891), pp. 72–82.

other portions of the delta may be dry and barren during a greater portion of the year. The decaying material of such fresh-water swamps, being preserved by the water covering, will serve to deoxidize the iron to the ferrous state, and even if the carbon is not sufficient in amount to color by its balance the argillaceous strata to brown or black, its former presence will still be indicated by gray or green bands of shales. Thus delta regions of subarid climates are peculiarly liable to be forming deposits which will ultimately become variegated shales, in which maroon, deep red, or vermilion bands will pass, sometimes almost without change of texture, into bands of grayish-white or green. An example of such variegated strata recently made is described by Huntingdon as having formed in the basin of eastern Persia and Sistan.[1]

The seaward portion of the delta surface is also frequently covered between the distributaries by brackish or salt-water lagoons and bays, as in the Nile and Mississippi deltas, protected from the waves and possibly containing considerable life of estuarine types, whose decay will lead in the same manner to variegated shales.

In truly arid climates, however, such river or sea lagoons are the seats of progressive evaporation giving rise to such salt pools as front the northern portion of the Caspian Sea or the recent gypsum deposits of the Isthmus of Suez. The degree of aridity and of the severance of the lagoons from the sea will determine the kind and amount of the chemical precipitation. It would seem, therefore, that the mud-cracked red beds originating on the delta surface of an arid climate should frequently be interstratified with mud-cracked beds holding salt or gypsum, a less arid condition leading more usually to the production of variegated shales.

MUD-CRACKS OF THE LITTORAL ZONE

Discussion as to present origin.—The littoral zone is one of the most sharply delimited of the natural physiographic divisions, forming a narrow belt between the sea and the land and defined here as comprising the zone between the average highest and lowest tides of the month. To form mud-cracks the deposit must be exposed to the sun or air sufficiently long to be dried out to such a depth

[1] *Carnegie Institution Publications* (1905), pp. 285 ff.

that the underground capillary rise is no longer able to keep the surface wet. This time limit will vary with the climate and the texture of the clay, but there may be immediately excluded all that portion of the littoral which is wet twice per day; in other words, all that portion of the littoral below the upper limit of the neap tides. This may be modified to some extent by strong off-shore winds. In the temperate zone such winds, being usually of a cyclonic nature, are frequently accompanied by rain; but where not, it is possible that by this means the tidal rise may be prevented from reaching its normal level by some feet and mud-cracks formed in the meantime somewhat below the usual level. In the latitudes of monsoon winds such effects might be seasonal, as is noted in the Runn of Cutch on the southeastern side of the Indus delta. Off-shore winds, therefore, will permit a wider development of mud-cracks over the upper portion of the littoral zone, but it is not probable than any appreciable areas below the level of mid-tide should be laid bare, dried, and cracked by such means. Neither has such an effect been described.

In tideless seas the fluctuations of level due to storms are important. Where there is an open reach of water, however, the waves which develop upon its surface break off-shore at a depth which the writer has seen stated somewhere as half the height of the wave below the trough of the same. This action maintains an open sea and an effective working depth, since the waves as soon as they drag on the bottom scour it out and carry the material partly on to the beach, partly into deeper water. In order, then, that any appreciable stretch of bottom normally covered by water should be laid bare, the change of water level between the on-shore and off-shore storms would have to equal at least the height of the waves of the on-shore storms.

As an instance of changes of level under favorable circumstances may be mentioned those of Lake Erie, a narrow body of fresh water 245 miles long lying in a northeast and southwest direction and therefore subject to heavy gales blowing the length of the lake from both directions. As a result Whittlesey has noted a change of level at Buffalo of $15\frac{1}{2}$ feet between flood water and low water.[1] At intermediate points such as Erie and Cleveland there is naturally

[1] Dana, *Manual of Geology*, p. 202.

but little change of level. Even at the points of extreme change a lowering of eight feet below the normal level lays bare but a narrow margin, insignificant in comparison with the total area of this relatively shallow lake. In addition it is observed that such extreme conditions are never of long continuance. Therefore, until instances are cited to the contrary, it must be considered that in all bodies of open water the normal wave action maintains such a depth that off-shore gales cannot lay bare any broad tracts of bottom. Partly land-locked lagoons may in such cases run dry, but such can only form a broader fringe within the actual limits of the land. The border flood zone of tideless seas is therefore not so much due to off-shore winds as to those which blow on-shore. Such may occasionally flood wide belts of lowland, as is seen to take place around the shores of the Gulf of Mexico. By such means in tideless seas mud-cracks may originate above the normal level of the water and therefore upon the land surface, but not to any appreciable extent below the line of mean water.

In the case of the Mississippi the possibilities for the formation of mud-cracks are doubtless somewhat increased by the presence of the mud lumps described by Hilgard, convex or low conical elevations, sometimes 100 feet or more in diameter, showing their tops at the surface. These occur in the shallow waters within one to three miles of the main channel at the mouth of the Mississippi River. They originate in upheavals of the soft but tough bottom. Once formed they discharge mud from the top, the successive layers being but a fraction of an inch thick.[1] These appear to be exceptional phenomena, however, and could hardly be appealed to to account for the structure of extensively mud-cracked formations.

Returning to the consideration of seas with notable tidal ranges it is doubtful if under any climatic conditions mud-cracks could be made upon surfaces left bare by the tides for less than thirty-six hours; but as offshore winds may succeed for a couple of days or more in preventing flooding above the line of neap-flood tide, that may be taken as the limit below which mud-cracks cannot form. Taking the relative heights of the neap and spring tides above the mid-tide line as 4 to 7, this gives 21.5 per cent. or approximately

[1] J. D. Dana, *Manual of Geology* (1895), p. 197.

the upper fifth of the littoral zone as the greatest possible limit over which mud-cracks may form. The upper fifth in level may, however, comprise much more than a fifth of the area, since the salt marshes are especially developed near this level. This indicates that the more favorable places for the development of mud-cracks are either those comprising extensive salt marshes, or regions of unusually great tidal range. As an example of the latter may be cited the Bay of Fundy as pointed out by Lyell.[1]

> On the borders of even the smallest estuaries communicating with the bay, in which the tides rise sixty feet and upwards, large areas are laid dry for nearly a fortnight between the spring and neap tides, and the mud is then baked in summer by a hot sun, so that it solidifies and becomes traversed by cracks, caused by shrinkage. Portions of the hardened mud may then be taken up and removed without injury. . . . . When a shower of rain falls, the highest portion of the mud-covered flat is usually too hard to receive any impressions; while that recently uncovered by the tide near the water's edge is too soft. Between these areas a zone occurs, almost as smooth and even as a looking-glass, on which every drop forms a cavity of circular or oval form, and, if the shower be transient, these pits retain their shape permanently, being dried by the sun, and being then too firm to be effaced by the action of the succeeding tide, which deposits upon them a layer of new mud.

In connection with fossil rain-prints this calls attention to another factor in the problem of fossil foot-prints and rain-prints, structures often associated with mud-cracks, and that is the necessity of drying and hardening before the next invasion of waters which would otherwise wash out the newly made record.

Not wishing to draw an artificial distinction, however, as mud-cracks belonging to the littoral zone may be here included those made from tides of abnormal rise, especially where the water is driven upward by powerful storms. But where flooding of erosion slopes takes place the mud deposited will be ultimately washed away. Where flooding of a river flood-plain takes place, the sea temporarily invades a region which is periodically flooded by fresh water, and therefore mud-cracks in such regions are not distinctive marks of the occupancy of the sea.

It is seen then that exceptionally high tides are not important as necessary conditions for the making of mud-cracks.

[1] "On Recent and Fossil Rains," *Quarterly Journal Geological Society*, Vol. VII (1851), p. 239

As a final exception may be noted the effect of the previously mentioned monsoon winds, as seen on the Runn of Cutch, southeast of the delta of the Indus. In this case winds blowing steadily on-shore for months at a time raise the sea-level sufficiently to flood with sea-water large tracts of marshy country which during another portion of the year become an arid desert. Such conditions are, however, very exceptional and probably are most likely to occur broadly where rivers have previously built up alluvial plains, so that this seasonal extension of the littoral zone may only take place in connection with the continental deposits of rivers.

As the season of off-shore monsoon winds, during which the mud-cracks form, should be normally a season of aridity, it is likely that saline deposits from evaporated sea-water should frequently be associated with the mud-cracks. This is notably the case in the Runn of Cutch. The two features are also associated in the saline beds of New York. If the climate on the contrary is a pluvial one, the rain which would wash off the residual sea-water would also prevent the formation of mud-cracks from the sea-water *as a cause.*

To sum up: it is seen that mud-cracks are confined to an upper fraction of the littoral zone, and where occasionally formed beyond it by inundations of the sea only attain a broad development at the present time in arid regions where continental river deposits have been previously built. In this case the mud-cracked strata should be at least frequently saliferous.

Nature of the geological record.—The nature of the geological record and the features which distinguish mud-cracks of the littoral zone from those made under other conditions may be gathered from the preceding discussion of the conditions of present occurrence. The zone itself marks the transition between a subaërial and a subaqueous surface, in the case of deltas each nearly horizontal but at different levels. When the delta deposits of these three regions are seen in cross-section, the littoral will be a transition belt between continental and marine deposits. As the seashore during the accumulation of the strata was ordinarily a shifting line, as seen in cross-section, it will pass nearly horizontally between the two. If the subsiding land was receiving no river deposits, the lower surface will be an erosive surface represented by an unconformity. If the land

surface had been one of river building it may underlie or overlie the littoral and marine deposits according as to whether the delta was retreating owing to subsidence or advancing owing to river building. But in either case the physical conditions of accumulation are so different upon the land and beneath the shallow sea that there is to be expected a marked contrast in the character of the contiguous continental and marine deposits.

Not only will the littoral zone be narrow and transitional in nature compared with the regions which border it on either side, but, as shown in the preceding article, its deposits are liable to suffer much destruction from the planing effect of the waves in the case of a subsiding land and are the first to suffer from subaërial erosion upon an emerging land. Only in the case of a delta building forth into a sea is there a good chance for the preserval of the littoral record. It has been further seen that mud-cracks are not a characteristic feature of the littoral, but can only originate upon its upper fifth or tenth, and in the places most favorable for ultimate preservation there is a grading into the land surface of the delta of which in arid climates the mud-cracks are more characteristic than of the littoral.

From these considerations it is seen that mud-cracks of littoral origin cannot be a characteristic or important feature of geological formations. They are by no means excluded as of occasional occurrence, but it would seem safe, where certain formations are dominated and widely characterized by mud-cracked shaly layers, to assign them to another origin and most probably to one upon a river plain receiving fluvial deposits.

To speak more particularly of the features which will be associated with the occasional mud-cracks of littoral origin may be noted the presence of beach structures of associated sands and muds, frequently fossils characteristic of the littoral zone, leaves and other débris from the land, rain-prints and the foot-prints of such land animals as frequent the shore. These will ordinarily be restricted to animals which seek food native to the littoral or cast up by the sea, as for instance the grubbing of swine for clams upon exposed mud flats, or birds which run over the flats and beaches for annelids or other small organisms.

The mud-cracks should be most frequently developed upon

coasts where the tides are high, and in this case the areas of salt marsh should be rather frequently cut up by wide and deep tidal channels filled with coarser material. Yet in most mud-cracked formations such erosion of deep channels across the mud-cracked layers is conspicuously absent.

Under the subject of mud-cracks of fluvial plains the subject of variegated shales was discussed and it was concluded that in those formed under a subarid climate the conditions were especially favorable for their production. Before closing the present topic, therefore, the subject should be again mentioned, in order to find if they may not form equally readily in the littoral zone or even in estuarine or open sea portions of the zone of marine deposits. Along the littoral somewhat the same conditions of variable exposure to the air exist as upon flood plains. Below the line of low tide, however, extensive tracts are never exposed to the air except by broad changes of level, and local variations in the amount of organic matter present, to which variegated shales are presumed to chiefly owe their origin, will depend upon conditions of current and influx of sediment. Variegated colors should therefore be associated more markedly with variations of texture and composition than is necessarily the case with the deposits upon flood plains; changes more analogous with the contrast between channel sands and true flood-plain muds.

That red muds as well as blue muds of the terrigenous zone may form on ocean bottoms is indicated by the red muds chiefly found off the Brazilian coast. "Its red color is thought to be due to the great amount of hydrous peroxide of iron brought to the sea by the rivers and which cannot be reduced by organic matter, as in the case of the blue mud. The area covered by it is, however, small, and is estimated at about 100,000 square miles,"[1] while the blue muds cover some 14,000,000 square miles.

Variegated shales may therefore originate in any zone of sedimentation and under any depth of water, but those of marine origin are due to broad and slow changes upon the land and should not show any of the local variations and partial independence between color and stratification which may mark the deposits of a flood plain. Within limits variegated shales may be considered, therefore, as rather characteristic of continental and littoral deposition.

[1] W. B. Clark, *Geological Survey of New Jersey, Annual Report*, 1892, p. 223.

CONCLUSIONS ON GEOLOGICAL SIGNIFICANCE OF MUD-CRACKS

From the preceding analysis of the origin of mud-cracks, as observed at the present time and the conditions under which they would be geologically preserved, it would seem that next to coal beds formed *in situ*, or abundance of land fossils belonging to the animal kingdom, that mud-cracks form one of the surest indications of the continental origin of argillaceous deposits. The structure is also seen most commonly to originate under climatic conditions where the other tests are apt to fail.

It may be considered, therefore, that mud-cracked shales predominantly indicate former flood-plain deposits, usually on delta surfaces which have displaced shallow seas. Removed from the vicinity of the sea and occurring in continental basins with older rock rims, they may have originated as playa deposits and indicate a formerly truly desert climate.

More rarely mud-cracked shales may be found as transitional belts separating unlike formations and indicative of the sun dried margins of former lakes or seas. In any case the associated characteristics which have been pointed out should assist in arriving at a conclusion in regard to the particular conditions of origin.

PREVAILING INTERPRETATIONS

The prevailing views upon a subject are exemplified by the statements of the current textbooks and manuals. These not only guide the formation of views of the younger students of the subject, but represent the longer-established and verified opinions of the older body of scientists. While frequently specialists in various lines would regard the presentation of their departments even in the better textbooks as not strictly up to date, this is, on the whole, not without its benefits, since it is necessary for new knowledge to become seasoned with time before its exact place and importance can be assigned among the body of well-established principles.

It will be desirable in summing up the present subject to compare the conclusions just arrived at with those statements concerning the significance of mud-cracks which are given in the standard texts, and which it is believed have been largely influenced by the habit

of interpreting all sediments as marine unless there was positive evidence to the contrary. It is in no spirit of adverse criticism that this is done, but in order to call sharper attention to the degree of variance with the present conclusions and the desirability of confirming or modifying the latter by further observation and analysis.

Turning first to the work of the best known of American geologists: J. D. Dana, in his *Manual of Geology*[1] stated that mud-cracks are made on drying mud flats, but with customary insight was evidently careful not to restrict them entirely to the seashore, since on the next page he refers to them as well as rain-prints as made by "exposure above the water level at low tide, or at least a low stage of the waters." Thus Dana recognizes the possible continental origin, but places the emphasis, perhaps unconsciously, upon the sea-beach or estuarine origin.

Chamberlin and Salisbury in their *Geology* (1904), Vol. I, p. 466, state that "sediments are sometimes exposed between tides, or under other circumstances, for periods long enough to permit drying and cracking at the surface."

Sir A. Geikie in his *Text Book of Geology*, 4th ed. (1903), pp. 643, 644, speaks of mud-cracks as vestiges of shores of former seas and lakes, and one of the kinds of evidence showing that a locality was sometimes laid bare of water.

James Geikie, in his *Structural and Field Geology* (1905), p. 116, mentions the present occurrence of mud-cracks around the shores of inland seas and lakes, and states that the same action may take place on low flat beaches which are exposed to a hot sun during the retreat of the tide. Although lake shores are mentioned first, no discussion is given as to the relative geological importance of the two situations in producing mud-cracks.

In none of the preceding books is the possibility mentioned of mud-cracks being formed over flood-plains of rivers and apart from permanent bodies of standing water. Yet these authors are authorities upon the subject of sedimentation and sedimentary structures, and in Sir A. Geikie's *Text Book* especially, an appreciation is constantly shown of the importance of fluviatile formations. It remains a question, therefore, if this difference of view upon the significance

[1] P. 94; see also pp. 742, 745 (1895).

of mud-cracks is due to an inheritance of expression from the past or if undue importance has been given in the present paper to mud-cracks of continental, and especially of flood-plain, origin in arid and subarid climates.

In both LeConte's and Scott's textbooks no mention is made of mud-cracks originating by any other means save by the laying-bare of tidal flats, and in both it is used as an argument proving the estuarine nature of the Newark basins; and Scott discusses the question whether the basins were parts of one or two "continuous bodies of water," p. 445.

Recently Huntingdon[1] has spoken of sun-cracks and ripple-marks taken in connection with other features as initiating continental sedimentation of the Tertiary in Central Turkestan.

> It appears as though, after the retirement of the sea, the land was covered with great playas, on which water first stood in thin sheets, forming ripple-marks in the mud and then retired or was evaporated, allowing the surface to become sun-cracked. As time went on streams began to flow across the playas, at first slow and broad and able to cut only shallow channels which were afterward filled and covered, assuming the form of very thin lenses of a material slightly different from that of the surrounding playa strata. Then, as the strength of the streams increased, sand was deposited over the whole area, and the channels, now deep and distinct, were filled with gravel. Lastly gravel was deposited almost everywhere.

So far as the writer is aware the only attempt at a discussion of the several methods of origin of mud-cracks and the relative chances of their preserval is by Penck,[2] who points out that they, as well as foot-prints and rain-prints, occur on sea-beaches, over the flood-plains of rivers and the shores of interior seas, but that the surface bearing the markings must to a certain degree have hardened and consequently have remained as a land surface for a certain length of time in order that the impressions should not be washed out by the next invasion of waters. For that to be accomplished he states that the sea-coast is less favorable than the flood-plains of rivers and the margins of lakes. In the latter cases the exposed floor dries for weeks or months and attains a considerable hardness before being again overflowed.

[1] "Explorations in Turkestan," *Carnegie Institution of Washington* (1905), pp. 164, 165.

[2] *Morphologie der Erdoberfläche* (1894), Vol. II, pp. 25, 26.

ILLUSTRATIVE GEOLOGICAL APPLICATIONS

In the preceding paper under the heading of "The Relations of Continental and Marine Sedimentation through Geological Time," it was concluded, not from a detailed study of the strata, but entirely from the broader relations at present prevailing, that at certain times in the past continental sedimentation should have played an important rôle, especially in the form of fluviatile deposits filling interior basins or displacing epicontinental seas. Having made this present examination of the different methods by which mud-cracks may originate, together with some of their associated characteristics, it will be well to apply it as a test to the conclusions of the preceding paper. If the result is a confirmation, there will thus be two largely independent lines of reasoning which arrive at the same result; a result in which therefore correspondingly more confidence may be placed.

MUD-CRACKED FORMATIONS OF THE PRE-CAMBRIAN

In both northwestern Montana and northwestern Arizona occur a series of predominantly arenaceous and argillaceous formations of great thickness which are distinctly older than the Middle Cambrian, since these lower formations were gently folded and base-leveled before the transgression of the Middle Cambrian sea. Yet these terranes are remarkably free from metamorphism and still retain their original characters. For this reason they are selected for illustration and briefly described. It was suggested in the preceding article that on account of the general nature of the deposits and the fact that the early Cambrian as well as the immediately pre-Cambrian were periods of great continental extension, the hypothesis of subaërial and fluviatile origin for certain formations should be at least entertained until disproved. It is now proposed to describe certain features of these formations in detail in order to arrive at some conclusion in regard to their continental, littoral, or marine origin, the conclusions being drawn after the presentation of the details.

PRE-CAMBRIAN FORMATIONS OF MONTANA

These are described by Walcott under the title of the "Belt Terrane"[1] and by Willis as the "Algonkian of the Lewis and Liv-

[1] Pre-Cambrian Fossiliferous Formations," *Bulletin Geological Society of America*, Vol. X, pp. 201, 215.

ingston ranges."[1] The two districts described above are about 150 miles apart in a general north-northwest and south-southeast direction; and as the intermediate region has not been studied in detail, Willis does not pretend to correlate closely the several formations described by him in the northwest with those described by Walcott from the district near Helena, but the similarity of sequence is sufficiently striking to warrant placing them in juxtaposition as is done below.

Belt Formation, Helena Region—Walcott	Thickness in feet
Marsh shales	300
Helena limestone	2,400
Empire shales	600
Spokane shales	1,500
Greyson shales	3,000
Newland limestone	2,000
Chamberlain shales	1,500
Neihart quartzites and sandstone	700
	12,000

Algonkian of Northwest Montana, Lewis and Livingston Ranges—Willis	Thickness in feet
Kintla argillite	800+
Sheppard Quartzite	700±
Siyeh limestone	4,000
Grinnell argillite	1,000 to 1,800
Appekunny argillite	2,000+
Altyn limestone	1,400+
(Bottom of limestone not exposed)	
	9,900 to 10,700

Brief descriptions of these formations are quoted as follows, those of the equivalent formations of the two localities being placed together:

Neihart quartzite and sandstone. Helena region, Little Belt Mountains.—In this formation are included the reddish, coarse sandstones, with interbedded dark greenish layers of fine-grained sandstone and shale, beneath the Chamberlain shales. The lower 400 feet of the formation is a massive, sometimes cross-bedded quartzite, which, in some of its members, where unaltered, is a compact, hard sandstone. The prevailing color is pinkish-gray on the freshly exposed surface, with dark and iron-stained weathered surface. Occasional layers of a fine conglomerate occur in some portions near the contact with the gneiss.[2]

About 300 feet above the base the character of the formation changes. The pink and white pure quartzites are replaced by more thinly bedded rocks, no longer of pure arenaceous material, but containing an admixture of greenish mica, which higher in the group forms the layers of mica shales interbedded with the quartzite. The higher strata are still more impure and the quartzite beds are but six to twelve inches thick, blackened by carbonaceous material that now forms a prominent feature of the intervening shales, becoming increasingly abundant until the latter rocks are true black shales in which the green mica no

[1] "Stratigraphy and Structure, Lewis and Livingston Ranges, Montana," *ibid.*, Vol. XIII, pp. 316–24.

[2] *Bulletin Geological Society of America*, Vol. X, p. 204.

longer shows. At the same time the quartzite beds decrease in thickness and purity, while the interbedded shale increases in thickness and purity, so that an arbitrary line must be drawn separating the two formations.[1]

Chamberlain shales, Helena region, Little Belt Mountains.—This formation is composed of a series of dark silicious and in places arenaceous shales. Ripple-marks, mud-flows, and sun-cracks were occasionally seen, but no traces of life were observed. The dark shales frequently form low cliffs along the canyon side, near the beds of the streams.[2]

Newland limestone, Helena region, Little Belt Mountains.—At the typical locality on Newland Creek the limestones are thin bedded, the layers averaging from two to six inches, with shaly partings of variable thickness between them. In the section of Sawmill Canyon, near Neihart, the layers are somewhat thicker, more impure, and with a greater number of beds of interbedded shale. The prevailing color of the limestone is dark bluish-gray on fresh fracture, and buff to straw color on the weathered surface.[3]

Altyn limestone, Lewis and Livingston Ranges.—Limestone, of which two members are distinguished; an upper member of argillaceous, ferruginous limestone, yellow, terra-cotta, brown, and garnet-red, very thin-bedded; thickness about 600 feet; . . . . and a lower member of massive limestone, grayish-blue, heavy-bedded, somewhat silicious, with many flattened concretions, rarely but definitely fossiliferous; thickness, about 800 feet.[4]

Greyson shales, Helena region, Little Belt Mountains.—Dark-colored, coarse, silicious, and arenaceous shales, passing above into bluish-gray, almost fissile shale, which, when broken up, weather to a light gray fissile shale, resembling a poor quality of porcelain. These in turn are succeeded by dark gray silicious and arenaceous shales, with interbedded bands of buff-colored sandy shales and occasional layers of hard, compact, greenish-gray and drab silicious rock. At the base of this series, in Deep Creek Canyon, a belt of quartzites occurs, interbedded with shales, the base of the quartzites showing ten feet of interformational conglomerates, composed of sand and pebbles up to eight inches in diameter, and derived from the subjacent Belt rocks.[5]

Appekunny argillite Lewis and Livingston Ranges.—The Appekunny argillite is a mass of highly silicious, argillaceous sediment approximately 2,000 feet in thickness. Being in general of a dark gray color, it is very distinct between the yellow limestones below and the red argillites above. The mass is very thin bedded, the layers varying from a quarter of an inch to two feet in thickness. Variation is frequent from greenish-black argillaceous beds to those which are reddish and whitish. There are several definite horizons of whitish quartzite from fifteen to twenty feet thick. The strata are frequently ripple-marked, and occasionally coarse grained, but nowhere conglomeratic.[6]

[1] W. H. Weed, *Geology of the Little Belt Mountains*, pp. 281, 282.

[2] *Bulletin Geological Society of America*, Vol. X, p. 206.

[3] *Ibid.* [4] *Ibid.*, Vol. XIII, p. 317. [5] *Ibid.*, Vol. X, p. 206.

[6] *Ibid.*, Vol. XIII, p. 322.

Spokane shales, Helena region, fifteen miles east of Helena.—The Spokane shales occur as massive beds of silicious and arenaceous shales of a deep red color. The arenaceous shaly portions frequently thicken up into thin layers of sandstone. The shales break down on exposure, but they are usually sufficiently firm to resist erosion and form strongly marked slopes and cliffs.[1]

The present writer had an opportunity in 1901 of examining the Spokane about 20 miles northwest of Helena and found the shaly layers frequently mud-cracked.

Grinnell argellite, Lewis and Livingston Ranges.—A mass of red rocks of predominantly shaly argillaceous character is termed the Grinnell argillite from its characteristic occurrence with a thickness of about 1,800 feet in Mount Grinnell. These beds are generally ripple-marked, exhibit mud-cracks and the irregular surfaces of shallow water deposits. They appear to vary considerably in thickness, the maximum measurement having been obtained in the typical locality, while elsewhere to the north and northwest not more than 1,000 feet were found. It is possible that more detailed stratigraphic study may develop the fact that the Grinnell and Appeknuny argillites are really phases of one great formation, and that the line of distinction between them is one diagonal to the stratification. The physical characters of the rocks closely resemble those of the Chemung and Catskill of New York, and it is desirable initially to recognize the possibility of their having similar interrelations.[2]

Empire shales, Helena region, twenty miles northwest of Helena.—These are greenish-gray massively bedded, banded, silicious shales.

Helena limestone, Helena region, Helena.—The Helena limestone formation is composed of more or less impure bluish-gray and gray limestone, in thick layers, which weathers to a buff and in many places to a light gray color. Irregular bands of broken oölitic and concretionary limestone occur at various horizons. Bands of dark and gray silicious shale and greenish and purplish argillaceous shale are interbedded in the limestones. These bands are from half an inch to several feet in thickness. There are also beds of thinner bedded limestones, especially toward the top of the formation.[3]

Siyeh limestone, Lewis and Livingston Ranges.—Next above the Grinnell argillite is a conspicuous formation, the Siyeh limestone, which rests upon the red shales with a sharp plane of distinction, but apparently conformably. The Siyeh is in general an exceedingly massive limestone, heavily bedded in courses two to six feet thick like masonry. . . . . Occasionally it assumes slabby forms and contains argillaceous layers. It is dark blue or grayish, weathering buff, and is so jointed as to develop large rectangular blocks and cliffs of extraordinary height and steepness. Its thickness, as determined in the nearly vertical cliff of mount Siyeh, is about 4,000 feet.[4]

[1] *Bulletin Geological Society of America*, Vol. X, p. 207.

[2] *Ibid.*, Vol. XIII, p. 322.

[3] *Ibid.*, Vol. X, p. 207. [4] *Ibid.*, Vol. XIII, p. 323.

Sheppard quartzite, Lewis and Livingston Ranges.—A distinctly sandy phase of deposition succeeding the extrusive rhyolitic eruption capping the Siyeh limestone has resulted in a quartzite which is very roughly estimated to have a thickness of 700 feet.[1]

The present writer has observed a basal quartzite to the Marsh shales in a similar stratigraphic relation upon Greenhorn Mountain, sixteen miles northwest of Helena. But the occurrence of the quartzite was lenslike and not persistent for many miles.

Marsh shales, Helena region.—At Helena there is a thickness of about 250 feet of shales and thin-bedded sandstones of the Belt Terrane above the Helena limestone and beneath the Cambrian sandstones. The same bed, on the north side of Mount Helena, is reduced to 75 feet in thickness, but to the northwest the formation increases in thickness to 300 feet or more.[2]

Kintla argillite, Lewis and Livingston Ranges.—Argillite and quartzite, thin-bedded, maroon red, ripple-marked, and sun-cracked, containing casts of salt crystals; also occasional beds of white quartzite and some calcareous; thickness 800 feet; no upper limit seen.[3]

The Kintla formation closely resembles the Grinnell, and represents a recurrence of conditions favorable to deposition of extremely muddy, ferruginous sediment. The presence of casts of salt crystals is apparently significant of aridity, as the red character is of subaërial oxidation. The formation has an observed thickness of 800 feet, but no overlying rocks were found. Its total thickness is not known, and the series remains incomplete.[4]

Discussion.—The very similar general nature of these formations at a distance of 150 miles from each other indicates similar conditions of accumulation over wide areas, though it is possible of course that the stratigraphic cycle was not strictly contemporaneous in the two regions. The volume of material which must have been eroded to supply these sediments was far greater than the volume of the sediments, since the one kind of sediments of any epoch, occurring at *both* localities, represents but a portion and, in the case of the limestones and quartzites, but a small portion, of the rock masses whose erosion supplied the material.

Taking Clarke's figures[5] of the average amounts of the oxides and common minerals in the "primitive crust of the earth" it is seen that an approximately pure dolomite which should contain all of

[1] *Ibid.*, p. 324.

[2] *Ibid.*, Vol. X, p. 207.

[3] *Ibid.*, p. 316.

[4] *Ibid.*, Vol. XIII, p. 324.

[5] "Analysis of Rocks, Laboratory of the U. S. Geological Survey," *Bulletin U. S. Geological Survey No. 168* (1899), pp. 14, 16.

the lime and magnesia of a primitive rock mass would contain but about one-tenth of the original, and in volume, allowing for the carbon dioxide in combination with bases, would roughly represent about a fifth of the original. In this case, however, since the material has been deposited from solution, it does not signify a necessary origin from contiguous land masses.

The average igneous rock, containing, according to Clarke, 10 per cent. of quartz, a pure quartzite will represent less than one-eighth of the original rock mass, but an argillite, containing variable amounts of the original quartz and additional water and carbon dioxide combined with the bases, represents a far higher, but indefinite, proportion of the original rock mass. Quartzites and argillites, however, since they cannot be transported across deep bodies of water imply contiguous land. The great thickness and similarity of the arenaceous and argillaceous formations over a wide area point to an originally still more widely spread character, since there is no indication that these districts were near the original limits. But their volume indicates deep erosion of a correspondingly extensive contiguous land. The formations do not show the local variations and conglomeratic nature which would indicate the erosion of a nearby mountain range, and therefore the denudation must have taken place from a wide area. The similar formations which are known to exist in British Columbia, Utah, Nevada, California, and Arizona emphasize still further the profound erosion of widespread adjacent land masses of late pre-Cambrian time.

Thus a detailed examination of the composition and texture of these Montana formations allows inferences confirming *for this region* the statements made in the previous article from more general grounds concerning the wide development of the continents in the later pre-Cambrian times.

In regard to the topographic and sedimentary cycles expressed by the succession and character of the formations it is seen that the two great limestones represent long-enduring incursions of the sea, while the quartzites and argillites represent the uplift and erosion of neighboring lands of large area.

The Neihart quartzite.—The cleanness and partially deferrized character of the basal formation, the Neihart quartzite, indicates shallow water off-shore deposit, subject to the prolonged sorting

and attrition characteristic of the work of currents and waves or of desert winds resulting in the accumulation of dune sands. The latter idea is perhaps made improbable by the transition into, and alternation with, the deoxidized and carbonaceous lower members of the Chamberlain shales.

The Chamberlain shales grade, on the one hand, into the underlying quartzite and, on the other, into the Newland limestone. These relations, in addition to the dark silicious and occasionally arenaceous character and occasional ripple-marks, suggest a quiet offshore formation. The mud-cracks noted by Walcott may be either of littoral or fluvial origin, but in either case imply a nearby land. The lack of a more arenaceous character may be due, therefore, to a topographic old age and lessened stream gradients of the land, or to the river material having been borne from a great distance.

Newland and Altyn limestones.—The inauguration of the era of the Newland and Altyn limestones may be due as much to the lack of supply of mechanical sediments as to subsidence and incursion of the sea.

Greyson and Appekunny argillites.—Following the limestone came some 2,000 to 3,000 feet of Greyson and Appekunny argillites. The generally dark gray color, thin-bedded lamination, occasional ripple-marks, and quartzitic strata suggest the submarine deposits poured into a sea as a result of the re-elevation of a contiguous land.

The association with the limestone below, the absence of conglomerates and observed mud-cracks, and the contrast in color with the deep-red and mud-cracked formation above all tend to confirm this interpretation.

The Spokane and Grinnell argillites, from 1,000 to 2,000 feet in thickness, on this view represent subaërial delta deposits over a region where sedimentation had gained upon subsidence to such an extent as to fill up and exclude the sea. In contrast to the inferior argillites are to be noted the highly oxidized character indicated by the deep red color, the frequent alternations of sandstone strata, and especially the widespread occurrence of mud-cracks. These are not sparingly present and developed in strata transitional between two distinct types, as would be characteristic of mud-cracks of the littoral zone, but on the contrary are developed in the normal red shales. Furthermore, the exposed sections show throughout a

marked sameness in color and a similar repetition of argillaceous and arenaceous beds. The areal extent, the fineness and evenness of grain, combined with the evidences of aridity, bespeak an extensive delta fan, comparable in size and climatic environment to those of certain of the larger Asiatic rivers of the present time.

The lack of knowledge as to the extent and relations of the formation will not allow of a closer comparison, but it is seen that it represents the continental culmination of the sedimentary cycle as the preceding Newland and Altyn limestones represented the opposite or marine phase.

The cycle appears to be less dependent here upon a mere transgression and recession of the sea as the active agent, than upon the wasting-away and the rejuvenation of adjacent land masses, which, upon being re-elevated, supply such a flood of sediment as to crowd back and dispossess the sea, the subsidence of the geosyncline going forward more or less continuously but at a variable rate.

The succeeding formations of this terrane indicate a repetition of this cycle, the Empire shales, showing greens and grays and passing into the upper limestones, doubtless represent the submarine deposits made during the transgression of the sea across the subsiding former delta surface. Then followed several thousand feet of limestone formation. This is largely thin bedded and shaly in the upper portions in the Helena region and various features described elsewhere suggest that it was largely accumulated in a shallow sea. This limestone was succeeded in places by quartzites which suggest wave-sorted deposits, and finally by a deep red mud-cracked series of argillites, somewhat similar to the Spokane-Grinnell formation, suggestive once more of land deposition under conditions of aridity. The thickness of this formation varies widely, the upper surface being a base-level erosion surface upon which is superimposed the Middle Cambrian marine transgression across a far-reaching and topographically ancient land.

THE GRAND CANYON SERIES OF ARIZONA

Leaving the preceding region and passing to the Grand Canyon of Arizona, some 750 miles south of Helena and some 950 miles south of the international boundary, a different series of rocks is

found to occur, but one holding a similar stratigraphic position, being embraced between the metamorphic formations of the Vishnu and Archean below and the unconformable Middle-Cambrian above. Walcott gives the series a total thickness of 11,950 feet, divided into two terranes, the upper or Chuar containing 5,120 feet of strata of which 285 feet are limestones and 4,835 feet brown to black or variegated shales and some reddish-brown sandstones. The lower or Unkar terrane attains a total thickness of 6,830 feet of which from 110 to 210 feet are limestones and the balance brown to vermilion sandstones and shaly sandstones with a basal conglomerate 30 feet in thickness. The Unkar is characterized by a great thickness of reddish-brown sandstones. The detailed section of the Unkar as given by Walcott follows, the italics being introduced:[1]

SECTION FROM THE SUMMIT DOWNWARD	FEET
1. *a*) Massive bed of gray to reddish magnesian limestone, passing below into a calciferous sand rock	50–150
b) Light gray, shaly sandstone	25
c) Irregular, massive beds of yellowish-brown sandstone	50
d) Partially crossbedded, fine grained, purplish-brown sandstone.	50
e) Reddish-brown sandstone and sandy shales, ripple-marked.	200
	475
2. Lava beds:	
a) Nine lava flows aggregating	770
b) Interbedded sandstones	30
At Chuar lava hill the lava beds are 1,000 feet thick.	
	800
3. Sandstones (upper)	
a) Shaly, vermilion, rather fine-grained sandstones, with intercalated bands of greenish-gray, followed below by 700 feet of vermilion beds of a uniform character, and massive beds with arenaceous, shaly partings, the massive beds breaking up into shale and sandstone on the talus slopes. *Ripple-marks and shrinkage cracks characterize the upper, shaly beds*	1730
b) The vermilion sandstones of *a*) pass into chocolate colored sandstones, that for 125 feet down unite in the general slope of the beds above. Below, a cliff is formed of five massive bands of chocolate-colored, slightly micaceous sandstone, separated by shaly sandstone partings of a greenish color below and a chocolate color above	925
c) Reddish-brown to chocolate, more or less shaly sandstone, 125 feet, underlain by 300 feet of friable sandstone and arenaceous and micaceous shale	425
d) Irregularly bedded, compact sandstone:	
Curiously twisted and gnarled layers	15
Massive, grayish layer	10
Light gray layer with reddish spots, friable, shaly in places	125
	3230

[1] "Pre-Cambrian Igneous Rocks of the Unkar Terrane," *Fourteenth Annual Report* (1894) U. S. Geological Survey, Part II, pp. 510–12.

4.	Sandstones (lower):	
a)	Compact, quartzitic, gray sand rock, 25 feet, with 65 feet of hard, compact sandstone	90
b)	Massive, compact, cliff-forming, brown, buff, and purplish-brown sandstone	1200
c)	1. Reddish-brown to vermilion, friable, shaly sandstone	200
	2. Brick-red, shaly sandstone	250
	3. *Brown, friable, shaly sandstone, ripple-marks and shrinkage cracks*	300
	4. Same in more massive layers, with fine, siliceous conglomerate	80
	(10 feet) at the base	80
		2120
5. *a*)	Light gray limestone with interbedded laminæ of quartzitic shale	8
b)	Brown sandstone with a bed of silicious conglomerate, 2 feet	30
c)	Reddish cherty limestone	10
d)	Reddish-brown limestone	2
e)	Dark, reddish-brown slate	5
f)	Light gray, compact shaly limestone	14
		69
6.	Dark, compact basaltic lava in one massive flow	80
7.	Light gray, compact shaly limestone with pinkish tinge between the laminæ; it is a little cherty near the base, or with thin, hard, interbedded layers of sandstone	26
8.	Silicious conglomerate formed largely of pebbles derived from the upturned edges of the prè-Unkar strata, upon which it rests unconformably	30
	Total thickness of the Unkar terrane	6830

Discussion.—The basal silicious conglomerate derived from the upturned edges of the underlying beds and followed by 175 feet of limestones containing a lava bed and some sandstone may be taken as a good indication of the invasion and continued presence of the sea.

It is noticed, however, that beginning 205 feet above the base are 10 feet of a fine silicious conglomerate which suggests a possible origin as a wave-sorted beach sand. Above this follows 370 feet of brown, friable, shaly sandstones showing ripple-marks and shrinkage cracks. These could be explained as of littoral origin by supposing that the subsidence and sedimentation remained exactly balanced so that this zone was the transition between the subaërial and submarine portions of a delta during the entire time of the deposit of the 370 feet. Even assuming a littoral origin, however, the immediate vicinity of a shore is implied and it seems a much simpler hypothesis to suppose that the mud-cracks were of flood-plain origin. Under this assumption the cracks could be more readily accounted for and it is not necessary to postulate an exact balance between the

subsidence, the marine planation and the delta building during all the time of accumulation, it being only necessary to assume that sedimentation remained in excess of subsidence and that the shore was a fluctuating line, of which this locality was continually on the landward side. These mud-cracked strata form the basal portion of the lower sandstones. Above them are 1,650 feet of red buff, brown, and vermilion sandstones and shaly sandstones similar in character, but not noted by Walcott as characterized by mud-cracks. The similar characters and especially the color of the iron oxide implying complete subaërial oxidation either before or after deposition suggest a continuance of the continental conditions. If deposited beneath the sea it would be expected that the continued wave action which affects the sandy deposits of shallow seas would, at least, in part, have separated the clay and iron from the grains of sand, producing cleaner gray quartzitic layers. Such a change is, in fact, noted in the compact, quartzitic, gray sand rock which separates the lower from the upper sandstone of the Unkar.

The question arises as to why the mud-cracks should be absent from the 1,650 feet of lower sandstones, if the latter were really of subaërial origin. The answer is that, even if the necessary periods of desiccation were present between the river inundations, mud-cracks need not necessarily arise. A sandy nature is unfavorable for their development, and the strata are much more sandy, on the whole, than in the case of the Spokane and Marsh shales of the Belt terrane. Again, a canyon wall is not a favorable place upon which to observe the bedding surfaces of gently dipping strata. It is furthermore possible that mud-cracked strata which could be observed by careful search were not noted, since Walcott was not conducting the examination with that end in view as a principal object. Finally mud-cracks which were noted were not always recorded in this necessarily brief synopsis of the strata, at least if they were off the line of the section, since on p. 515 of the article cited it is stated that at Chuar Lava Butte numerous ripple-marks and mud-cracks occur among the sandstones and shales covering the uppermost lava flow, yet mud-cracks at this horizon are not mentioned in the synopsis which has been given.

Returning to the description of the Unkar stratigraphic section,

the upper sandstones below the lava beds comprise 3,230 feet, nearly all being again vermilion, reddish-brown, or chocolate in color. Occasional partings of a greenish-gray are noted, and the upper shaly beds are characterized by ripple-marks and shrinkage cracks. It would seem from this that if the gray quartzite separating the upper and lower sandstones is, indeed, a beach and marine deposit, that the transgression was but temporary, the beach was pushed back and subaërial deposition continued.

Following this stage occurred a series of outpourings of lava, thin layers of sandstone separating most of the flows. The lava beds aggregate from 770 to 1,000 feet in thickness, varying this much in a distance of about four miles. The partings of shale and sandstone are widely distributed and of uniform thickness over considerable areas (p. 517) and on Chuar Lava Butte it is noted that the upper lava flow is capped by 35 feet of cholocate-brown sandstone and sandy shales with numerous ripple-marks and mud-cracks occurring among the layers (p. 515).

A study of the relations of the traps and interbedded sandstones with respect to the alternative hypotheses of marine or continental origin would probably offer some evidence in support of one view as against the other. The widespread character of the lava flows indicates that they were poured out over a level surface. The subaërial portion of a delta with a slope of normally not more than a foot per mile is more broadly level than the submerged portion, but, on the other hand, is also more cut by stream channels.

The more or less viscous nature of lava would cause the upper surface of the flows to depart from a true plane. If above the sea level the streams would tend to erode the upper surface to some extent and result in thicker deposits of sand and clays in the hollows of the upper surface, leveling it once more to grade. These effects might be less marked if the lava flows were poured out beneath the sea.

In the absence of field study with these points in view it seems best to leave the problem as an open question, but the mud-cracked layers covering the upper lava flow indicate rather strongly the subaërial origin of at least that particular sheet.

Above the last lava flow are found 250 feet of these apparently

land-deposited beds followed by 50 feet of irregular massive beds of yellowish-brown sandstone and 25 feet of light gray shaly sandstone. These by their contrast in color presumably represent the off-shore deposits of a transgressing sea and are followed by 50 to 150 feet of massive, gray to reddish magnesian limestone, closing the deposits of the Unkar terrane.

The detailed section of the following Chuar terrane is not quoted in full as the beds are not described by Walcott as mud-cracked, nor do most of them by their other characters strongly suggest subaërial deposition. As previously noted, they embrace 5,120 feet of strata of which 285 feet are limestones. The greater portion of the balance consists of brown to black, gray, or variegated shales, with some reddish-brown sandstones, often shaly. Deposition in off-shore waters beyond the reach of beach action is suggested as the mode of origin of much of the formation by the prevailing difference in color, the more shaly character, and the beds of limestone scattered at intervals through the entire terrane. Occasional transitions to shore deposits of an arid climate are similarly suggested by the variegated shales, and especially masses of white and pink gypsum found in a few localities in one horizon which consists of black argillaceous shale with chocolate and greenish, sandy and argillaceous shales beneath, carrying hard layers of sandstones.

A classification of the Chuar section into appreciably calcareous and arenaceous portions suggests three movements of subsidence with invasions of the sea and four periods of halting or possibly elevation with approach of the littoral to this region, the series ending with 125 feet of massive, reddish-brown sandstone, with irregular layers of similar color and containing numerous fragments of sandstone-shale of lighter color.

The thorough and accurate observations of Walcott have made it possible to give this discussion of continental as opposed to marine origin both for the Belt and Grand Canyon series, although the problem of a possible continental origin is not discussed in the original papers and possibly was not seriously in mind, since such a question had never been raised in regard to them. Since the facts have been freely quoted, however, it is also desirable to give the observer's interpretation, which is throughout that of a marine

origin. In regard to the upper lavas of the Unkar terrane Walcott states:

> The first coulée flowed over the level ocean bed, in which 5,000 feet of sediment, that now forms a reddish-brown sandstone, had accumulated on the upturned and eroded edges of the Archean, the few layers of limestone and the one flow of lava, 150 feet in thickness near the base scarcely serving to break the great sandstone series.[1]

Again the author states that

> The wide distribution of thin layers of sandstone, shale, etc., of uniform thickness over considerable areas indicates a relatively smooth sea bed at the time of the spreading of the first sheet of (the upper) lava over it; and that the sea was shallow, is shown by ripple-marks and the filling of sun-cracks.[2]

CONCLUSION ON THE NATURE OF THE PRE-CAMBRIAN SEDIMENTATION

In the absence of personal observation with the particular problem in mind any other interpretation than that given by Walcott should be held with reservation, but it has been shown that in view of the highly oxidized character of the sandstones of the Unkar terrane, and mud-cracks frequently found in the shaly beds, that the presumption is in favor of a continental origin and the burden of proof is rather upon those who would give the marine interpretation.

The discussion of these pre-Cambrian deposits but especially of the Montana occurrences, shows how completely in accord is the hypothesis of the dominant flood-plain origin of mud-cracks with the other marks of subaërial deposition in an arid climate. The mud-cracks are confined to just such formations as from other characteristics suggest a flood-plain origin and these formations are usually separated from the deposits of limestone by transitional formations which differ in color, in character, and in the absence of mud-cracks, suggesting the true submarine deposits originating between the shore and the open sea.

Assuming that a strong case has been made out for the continental origin of certain of these pre-Cambrian formations, it is seen that in the two regions examined the conclusion is justified which was reached from general considerations in the preceding paper—that the late pre-Cambrian being an aeon of wide continental extension should show in its epicontinental deposits a considerable proportion

[1] P. 504. [2] P. 517.

of subaërial origin. The two regions are unusually favorable for study in this particular, since, as previously noted, the deposits have been relatively little disturbed by later earth movements and the original sedimentary record has not been obliterated through the processes of metamorphism.

A general conclusion should be founded on a far wider study of occurrences, but such would run beyond the limits of this paper. It may be noted in passing, however, that the Montana region shows an unusual proportion of carbonate rocks, while the pre-Cambrian deposits over the world as a whole apparently are characterized by minor amounts of carbonates, rocks whose presence in notable proportions are usually the surest indication of truly marine conditions. Such a poverty in limestones may in a small measure be accounted for by a possible dominance of disintegration over decomposition in the erosion of those times, the lime thus in part not being set free and the disintegrated products giving rise upon metamorphism to a large proportion of gneisses, graywackes, and feldspathic schists, instead of quartzites, argillites and marbles.

Highly silicious rocks are, however, not uncommon, and the question arises as to where the corresponding quantities of salt, gypsum, and dolomitic limestones are to be found. In the long time elapsing since their origin these might have been completely leached out by subterranean waters, as Rutley has shown,[1] if they had remained near the surface in the zone of circulating waters. But the pre-Cambrian rocks are usually highly metamorphic and have been buried deeply in the zone of anamorphism during a considerable proportion of their existence, so that such an explanation can hardly apply to them in very much greater measure than to the Eopaleozoic limestones which remain in such abundance.

The bulk of the salt is doubtless still in solution in the sea and is a measure of the volume of erosion in those early ages in addition to that of later times. The corresponding dolomites, however, since they are apparently not found in proportionate abundance upon the continents must presumably repose within the limits of the present ocean basins.

[1] "On the Dwindling and Disappearance of Limestones," *Quarterly Journa Geological Society*, Vol. XLIX (1893), p. 372.

But as carbonate deposits are characteristic of the open sea, so are silicious, feldspathic, and argillaceous deposits dominant upon the land surface, and thus a separate argument is derived for the view that in pre-Cambrian times the continents possessed at least their present extension, an argument, however, which requires further testing in regard to the premises as to the poverty of limestones.

It would seem, therefore, that the 12,000 feet of the Belt terrane, consisting, as it does, of from 37 to 50 per cent. of dolomitic limestones is far from being an occurrence holding an unusual proportion of continental deposits and that the conclusion derived from its study in regard to their presence in important quantity is therefore susceptible of wider application.